International Journal of Agricultural
Science and Research (IJASR)
ISSN(P): 2250-0057; ISSN(E): 2321-0087
Vol. 5, Issue 6, Dec 2015, 67-78

MODELLING RUNOFF AND SEDIMENT YIELD FROM A SMALL FOREST WATERSHED IN SHIVALIK FOOT-HILLS USING WEPP MODEL

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ABSTRACT

Hydrologic models play an important role in understanding the erosion process, quantification of runoff and sediment yield at the watershed scale and to identify the best management practices. In this study, the WEPP watershed model has been applied to simulate storm wise runoff and sediment yield from a small forest watershed having an area of 21.3 ha located in Shivalik foot-hills. The watershed was divided into 35 hillslopes and 25 channels. Climate file was generated by CLIGEN software using observed meteorological data. For each hillslope and channel, soil, slope and land use management files were prepared. The sensitivity analysis of the model shows that the model output is sensitive to hydraulic conductivity, rill erodibility, inter-rill erodibility, and critical shear of the soil. The model was calibrated and validated using observed data on runoff and sediment yield pertaining to 22 storms (2001-2004). The model simulated storm runoff with reasonable accuracy as corroborated by low values of RMSE (4.59 mm), percent error (11.36) and high values of correlation coefficient (0.96), and model efficiency (87.54%). The model also performed satisfactorily in simulating sediment yield as indicated by the values RMSE of 0.33 Mg/ha, percent error 13.83, correlation coefficient of 0.85 and model efficiency of 83.18%. In quantifying total runoff and sediment yield, the percent simulation error was well within the acceptable limits. The results of the study indicate the suitability of the WEPP model for its future application in Shivalik foot-hills.

KEYWORDS: Forest Watershed, Hydrologic Models, Runoff Simulation, Sediment Yield Simulation, WEPP Model

Received: Oct 11, 2015; **Accepted:** Oct 20, 2015; **Published:** Oct 26; **Paper Id.:** IJASRDEC201510

Original Article

INTRODUCTION

The surface soil removed by wind or water causes land degradation and deteriorates the surface water quality. It threatens the most important and non-renewable resource i.e. the farmland that is suitable for cultivation. About 0.3-0.8% of the world's arable land has been rendered unsuitable for agricultural production (Biggelaar *et al* 2004, Lafond *et al* 2006). Soil erosion is more prominent in areas that are not covered by vegetation like the mountains and hill slopes that are tilled. The rain sweeps away the entire top soil with it thereby causing erosion. Besides removing a valuable resource, soil erosion leads to increased sediment flow into nearby rivers. All the water that reaches a stream and its tributaries carries sediment eroded from the entire area drained by it. A number of studies have been conducted across the globe at different spatial and temporal scales to understand and assess the underlying processes of soil erosion, sediment transport and deposition (Morgan 1986,

Rose 1993, Haan *et al* 1994, Brazier 2004, Gao 2008).

The Shivalik foot-hills which are a part of the Himalayan mountain chain, continuously run from Jammu, Pathankot, Kangra Valley, Hoshiarpur, Ropar, Sirmur district to Dehradun and finally end up at Bhabbar tracts of Garhwal and Kumaon. The Shivaliks are facing serious problems like soil erosion, degradation of water catchment areas which is reducing agricultural productivities. In the state of Punjab, an area of 5.38 lakh hectare which falls in the Shivalik foot-hills and locally known as kandi area, is considered to be one of the eight most degraded and fragile agro-ecosystems of the country (Dogra 2000). A large portion of monsoon rainfall (35-40%) goes as runoff in the torrents originating from the Shivalik foot-hills (Bhardwaj and Rana 2008). The annual erosion rate in the Shivalik foot-hills is more than 80 Mg $ha^{-1}year^{-1}$ and in some watersheds it is as high as 244 Mg $ha^{-1}year^{-1}$ (Singh *et al* 1992, Bhardwaj and Kaushal 2009). This clearly shows that some form of soil conservation or soil protection policy is needed urgently in this area for which it is essential to quantify sediment yield in the study area.

To increase the sustainable agricultural production, planned land use and conservation measures are needed to optimize the land and water resources. However, to achieve this, quantification of runoff and sediment yield from the problem watershed is must. Since it is often impossible to directly measure soil loss on every piece of land, and reliable estimation of runoff and sediment yield for remote and inaccessible areas are tedious and time consuming by conventional methods, it is therefore desirable that some suitable methods and techniques are evolved for quantifying the hydrological parameters from all parts of the watersheds. Use of mathematical hydrological models to quantify sediment yield for designing and evaluating alternate land use and best management practices in a watershed is a handy tool to understand and quantify the effects of specific management practices in a diverse ecosystem (Xevi et *al* 1997).

Several sediment prediction models have been developed to estimate sediment yield from a watershed, RUSLE, EPIC, ANSWERS, CORINE, ICONA, MIKE SHE, CASC 2D, AGNPS, CREAMS, SWAT and WEPP are a few among the models (Bhardwaj and Kaushal 2009). These models are site specific and have been developed for the climatic conditions prevailing in Europe. However, WEPP (Water Erosion Prediction Project) watershed model, which is an extension of WEPP hillslope model, is found to be capable of simulating runoff, estimating soil loss, and selecting catchment's management practices for conservation planning for field and small watersheds (Flanagan and Nearing 1995, Lane *et al* 1997). WEPP model which mainly considers overland flow is currently best suited to predict runoff and soil erosion on surfaces where overland flow dominates hydrologic processes.

The model has been used successfully worldwide (Yu and Rosewell 2001, Huang *et al* 1996, Amore *et al* 2004, Pieri *et al* 2007, Baigorria and Romero 2007, Shen *et al* 2009, Shen *et al* 2010) for estimating runoff and soil loss from different land use and crop management practices. Few studies have been conducted in India for quantification of runoff and sediment yield using WEPP model (Pandey *et al* 2008, Ramsankaran *et al* 2009, Singh *et al* 2009), wherein the model was calibrated and validated using the historical hydrologic data of small agricultural watersheds with medium slope. Although the WEPP model was used to simulate runoff under high rainfall and high slope conditions as prevailing in Shivalik foot-hills (Sharma 2012) but none of the studies has been conducted for simulating the sediment yield under such conditions. Thus, there is need to evaluate the performance of WEPP model for simulating sediment yield from small watersheds in Shivalik foot-hills for its future application in the area.

MATERIALS AND METHODS

Study Area Description

The watershed is about 15 km from Chandigarh located at a latitude of 30° 45’ North and longitude of 76° 45’ East, having area of 21.3 ha and an elevation of 370 m above mean sea level in Shivalik foothill region. The average annual rainfall is 1100 mm of which 80% is received during monsoon season only. The rainfall is highly erratic and occurrence of high intensity rainfall is a common feature. The area has a sub-humid type of climate. The mean slope of the watershed is 36.1%. The soil texture of the watershed is sandy to sandy loam, well drained, slightly alkaline with pH of 7.2 to 7.5 and low in nutrients. The hydraulic conductivity of these soils varied from 0.11 to 7.44 cm/hr in different slope directions and hillslopes. Soil texture, sand content, clay content, litter deposition (LD) organic carbon and cation exchange capacity in surface soils (0-20 cm) at different aspects and topographic locations of the watershed is shown in Table 1 (Yadav *et al* 2005). The watershed has a dense vegetation with an impoundment at the outlet. The watershed is being gauged for monitoring runoff and soil loss by Central Soil and Water Conservation Research and Training Institute, Research Centre, Chandigarh. Figure 1 shows the map of study watershed. *Acacia catechu*, *Dalbergia sissoo*, *Lantana camara* and bhabbar grass (*Eulaliopsis binnata*) are the dominant trees, shrub and grass species of the watershed.

Table 1: Soil Texture, Clay Content (%), Litter Deposition (LD) (Mg/Ha/Yr) and Organic Carbon (OC) (%) In Surface Soils (0-20 Cm) at Different Aspects and Topographic Locations of the Watershed

Reaches	Top				Middle				Bottom			
Aspect	Texture	Clay Content	LD	OC	Texture	Clay Content	LD	OC	Texture	Clay Content	LD	OC
East facing slope	Sand	8.8	23.0	1.09	Sandy loam	18.8	71.7	1.83	Sandy loam	19.8	71.7	2.00
North facing slope	Loamy sand	11.8	5.8	0.39	Sandy loam	17.8	10.9	0.89	Sandy loam	15.8	24.9	0.54
South facing slope	Sandy loam	14.8	9.6	1.95	Loamy sand	11.8	20.7	1.20	Loamy sand	10.8	15	1.01
West facing slope	Loamy sand	10.8	8.4	0.74	Sand	8.8	7.6	0.47	Sand	13.8	10.7	1.01

Source: Yadav et al 2005

Model Inputs

The major input files for WEPP watershed model application for simulating sediment yield are climate, soil, slope, cropping/management practices and channel files. Input file builders are provided in the model for all input data files except the climate input file where a program called CLIGEN is provided in the model which can be used to generate data series of any length. The watershed was divided into a total of 35 hillslopes and 25 channels (Figure 2).

Climate Input File

The climate input file provides for either single storm event or a continuous rainfall series. Actual data can be supplied, or a program called CLIGEN, a stochastic weather generator that produces daily time series estimates of precipitation, temperature, dewpoint, wind, and solar radiation for a single geographic point, based on average monthly measurement for the period of climatic record, like means, standard deviations, and skewness can be used where only rainfall statistics are available. Daily observed precipitation, maximum and minimum temperature for past years (2001 to 2004 for the watershed) were used in CLIGEN software to generate all the climatic data i.e. duration of precipitation, ratio

of time to rainfall peak/rainfall duration, ratio of maximum rainfall intensity and average rainfall intensity, daily solar radiation, wind velocity, wind direction and dew point temperature. Using CLIGEN program and average climatological parameters for the study area, climate file was generated by adding a new international station, named as Chandigarh. Data on daily rainfall, maximum temperature, and minimum temperature as observed in the studied watershed was used.

Soil Input File

Soil characteristics for each hillslope, including type of soil, hydraulic conductivity, soil albedo, initial saturation, number of soil layers, thickness, bulk density, sand, clay and organic matter percentage, rill erodibility, inter-rill erodibility, critical shear, etc. were provided in soil input file. Information on soil properties to a maximum depth of 1.8 meters (upto 8 to 9 different soil layers) can be used as input to the model through soil input file.

Slope Input File

The distance - elevation data was generated segment-wise for each hillslope from the topographic map of the watershed. The slope of each hillslope segment was calculated using the following formula:

$$\text{Percent slope S} = \frac{E_2 - E_1}{L} * 100 \tag{1}$$

Where E_1 = elevation of lower point (m), E_2 = elevation of higher point (m) and L = segment length (m).

The slope input file was prepared in the slope profile editor. Slope profile is plotted between distance and elevation. In the model, the slope file builder has the added advantage of allowing the user to graphically preview the slope profile.

Land Use and Management Practices Input File

The land management input file contains all the information needed by the WEPP model related to plant parameters (rangeland plant communities and cropland annual and perennial crops), tillage sequences and tillage implement parameters, plant and residue management, initial conditions, contouring, subsurface drainage, and crop rotations. The management file builder contains a large number of built in cropping pattern and management practices, which can be easily brought into our data file to suit the prevailing conditions of Shivalik foot-hills on each overland flow elements within a hillslope.

Channel Input File

Channel properties such as width and depth of channel, hydraulic properties, channel bank management details, soil characteristics, etc. were given as input data in channel input file. Channel soil, channel slope and management files were prepared for each channel segment. Procedure for preparation of channel input files is exactly the same as that for hillslope.

Statistical Analysis

The observed and predicted values of runoff and sediment yield on daily basis were compared by calculating statistical parameters namely: mean, standard deviation, percent error, coefficient of correlation, root mean square error, and Nash-Sutcliffe model efficiency, for calibration and validation of the model.

RESULTS AND DISCUSSIONS

Sensitivity Analysis of Model Parameters

Sensitivity analysis is a common technique used to assess model uncertainty in relation to errors in parameter estimation. It ranks model parameters based on their contribution to overall error in model predictions. Sensitivity analysis not only helps to identify the influence parameters but also quantify their influence on outputs. Moreover, for the purpose of model application, sensitivity analysis also determines the level of accuracy or precaution needed in determination of these parameters. The input parameters selected for the sensitivity analysis of the model were soil characteristics, viz., effective hydraulic conductivity, rill erodibility, inter-rill erodibility and critical shear.

The results of sensitivity analysis carried out on the input parameters for the watershed (Table 2) show that the runoff is sensitive only to effective hydraulic conductivity (K_e) with a sensitivity ratio of -0.302. Other parameters like rill erodibility, inter-rill erodibility and critical shear do not affect the predicted runoff. Rainfall infiltration increases with the increase in effective hydraulic conductivity (K_e) and decreases with decrease in effective hydraulic conductivity (K_e). Hence, runoff volume decreases when K_e is increased, and increases when K_e is decreased. Similarly sediment yield is most sensitive to the rill erodibility followed by inter-rill erodibility, effective hydraulic conductivity and critical shear as is evident from the values of sensitivity ratio in sediment yield simulation (Table 2). Sensitivity of the model to rill erodibility is highest for sediment simulation. This shows that the rilling process is dominant in high slope and high rainfall condition. Critical shear stress of soil has also influence on the model response for sediment yield as indicated by its sensitivity ratio of -0.173 (Table 2) for the watershed. In the erosion process, detachment of soil particle is a function of critical shear stress of soil. Erosion is considered to occur when hydraulic shear stress of flow exceeds the critical shear stress of the soil. Therefore, influence of critical shear stress on erosion is quite obvious. Interrill erodibility, rill erodibility and critical stress are considered in the model to calculate erosion that is, these parameters are dominant in erosion process. (Baffaut *et al*.,1997; Bhuyan *et al*.,2002; Pandey *et al*., 2008; Singh *et al*., 2011)

Table 2: Model Sensitivity to Different Input Parameters for the Watershed

Parameter	Soil Type	Calibrated Value	Range of Parameter		Sensitivity Ratio	
			-50%	+50%	Runoff	Sediment Yield
K_e (mm/h)	Sand	5.11	2.56	7.67	-0.302	-0.283
	Sandy Loam	12.53	6.26	18.79		
	Loamy Sand	5.31	2.67	7.96		
K_i(10^6 Kg/s-m^4)	Sand	8.4	4.20	12.6	0	0.438
	Sandy Loam	7.35	3.68	11.02		
	Loamy Sand	7.90	3.95	11.85		
K_r (s/m)	Sand	0.0248	0.0124	0.0372	0	0.603
	Sandy Loam	0.0102	0.0051	0.0153		
	Loamy Sand	0.0175	0.088	0.105		
τ_c (N/m^2)	Sand	2.0	1	3	0	-0.173
	Sandy Loam	2.7	1.35	4.05		
	Loamy Sand	3.2	1.60	4.80		

K_e: Effective hydraulic conductivity, K_i: Inter-rill erodibility, K_r: Rill erodibility, τ_c: Critical shear

Calibration of the Model

WEPP model has been calibrated to simulate runoff and sediment yield from a forest watershed in Shivalik foot-hills. The data of total of 22 storms for the watershed was available from the year 2001 to 2004, out of which 9 storms

were used for calibration and 13 for validation of the model. Soil parameters namely effective hydraulic conductivity, interrill and rill erodibility, and critical shear were considered for calibration in the present study. The values of parameters were chosen within the prescribed range (Flanagan and Livingston 1995) and were adjusted by trial and error basis.

The performance of the model was evaluated statistically by comparing observed and simulated values of runoff and sediment yield.

Runoff

The storm wise observed and predicted values of runoff for the watershed is plotted for the calibration period in Figure 3. The summary statistics of the observed and predicted storm wise runoff for calibration period for the watershed is shown in Table 3. For the watershed, the RMSE of 2.77 mm, correlation coefficient of 0.98, percent error of 6.52 and model efficiency (E_{NS}) of 93.79%, for the calibration period indicate reasonably accurate simulation of surface runoff by the model.

Table 3: Test Statistics for Runoff Simulation by WEPP Model during Calibration

Parameter	Watershed (Area = 21.3ha)	
	Observed	Simulated
Mean (mm)	13.43	12.17
Std. Dev. (mm)	10.13	9.13
Maximum (mm)	32.3	32.2
Total (mm)	120.94	109.56
RMSE (mm)	2.77	
Percent error (%)	6.52	
Correlation Coefficient	0.98	
Model efficiency (E_{NS})	93.79%	

Sediment Yield

The storm wise observed and predicted values of the sediment yield for the watersheds are plotted for the calibration period in Figure 4. The summary statistics of the observed and predicted storm wise sediment yield for calibration period for the watershed is shown in Table 4. The RMSE of 0.16 Mg/ha, correlation coefficient of 0.93, percent error of 9.16 and model efficiency (E_{NS}) of 86.06% for the calibration period indicate reasonably accurate simulation of sediment yield by the model.

Table 4: Test Statistics for Sediment Yield Simulation by WEPP Model during Calibration

Parameter	Watershed (Area = 21.3ha)	
	Observed	Simulated
Mean (Mg/ha)	0.95	1.00
Std. Dev. (Mg/ha)	0.43	0.45
Maximum (Mg/ha)	1.89	2.00
Total (Mg/ha)	8.61	9.02
RMSE (Mg/ha)	0.16	
Percent error (%)	9.16	
Correlation Coefficient	0.93	
Model efficiency (E_{NS})	86.06%	

Validation of the Model

Once the model is calibrated, proper validation of the model is essential for model testing before it could be applied for simulation of runoff and sediment yield. During validation, the performance of the calibrated model was judged

without any change in the input files except the climate file. The data on rainfall-runoff and sediment yield collected for the study watershed were used for the validation and quantification of runoff and sediment yield. The data of total of 22 storms was available from the year 2001 to 2004, out of which 13 storms (2003-2004) were used for validation of the model.

Runoff

The storm wise observed and predicted values of runoff for the watershed has been plotted along with corresponding rainfall amounts for validation periods in Figure 5. It is observed that the trend of the predicted values closely matches the trend of observed values of runoff. The total observed and simulated values of runoff for the watershed for the validation period was 180.93 mm and 174.5 mm respectively. Scatter plot for the storm wise observed as well as predicted runoff for model validation (Figure 6) show that the majority of data points are evenly distributed about the 1:1 slope line. The results of statistical analysis of runoff for watershed are presented in Table 5. For the watershed the RMSE of 4.59 mm, correlation coefficient of 0.96, percent error of 11.36, and model efficiency of 87.54% for validation period indicate reasonably accurate simulation of runoff by the model.

Table 5: Test Statistics for Runoff Simulation by WEPP Model during Validation

Parameter	Watershed (Area = 21.3ha)	
	Observed	Simulated
Mean (mm)	15.07	14.53
Std. Dev. (mm)	14.04	14.67
Maximum (mm)	43.57	46.97
Total (mm)	180.93	174.5
RMSE (mm)	4.59	
Percent error (%)	11.36	
Correlation Coefficient	0.96	
Model efficiency (E_{NS})	87.54%	

Sediment Yield

The storm wise observed and predicted values along with the cumulative values of the sediment yield for the watershed are plotted for the validation period in Figure 7. It is observed from that the trend of the predicted values closely matches the trend of observed values of sediment yield. The total observed and simulated values of sediment yield for the watershed were 7.59 Mg/ha and 7.96 Mg/ha, respectively for 13 storms used for simulation.

The scatter plot between the observed and predicted values of sediment yield for the watershed (Figure 8) shows that the data points are even and closely distributed along the 1:1 line except a few points which have not been predicted well by the model. This may be explained by the fact that the soil erosion process is highly complex phenomenon and is affected by interaction among rainfall, runoff, soil texture and structure, land use, land slope and conservation measures. Therefore, magnitude of randomness in storm wise values of sediment yield may be large. So, a hydrologic model is most likely to simulate annual values better than the storm wise values of sediment yield.

The results of statistical analysis of sediment yield for watershed are presented in Table 6. The RMSE of 0.33 Mg/ha, correlation coefficient of 0.85, percent error of 13.83 and model efficiency of 83.18% for validation period indicate reasonably accurate simulation of sediment yield by the model. Overall, the WEPP watershed model has been found to be quite suitable for simulation of runoff and sediment yield in Shivalik foot-hills.

Table 6: Test Statistics for Sediment Yield Simulation by WEPP Model during Validation

Parameter	Watershed (Area = 21.3ha)	
	Observed	Simulated
Mean (Mg/ha)	0.63	0.66
Std. Dev. (Mg/ha)	0.569	0.566
Maximum (Mg/ha)	1.86	1.45
Total (Mg/ha)	7.59	7.96
RMSE (Mg/ha)	0.33	
Percent error (%)	13.83	
Correlation Coefficient	0.85	
Model efficiency (E_{NS})	83.18%	

CONCLUSIONS

Based on the results of the study, the following specific conclusions have been drawn:

- The WEPP model has the capability to simulate runoff and sediment yield with reasonable accuracy in the Shivalik foot-hills.
- The model is highly sensitive to hydraulic conductivity while simulating the runoff, whereas, sediment yield is most sensitive to the rill erodibility followed by inter-rill erodibility, effective hydraulic conductivity and critical shear. Hence, extreme care must be taken in estimating and selecting these parameters for model calibration.
- The overall statistical model performance parameters namely RMSE of 4.59 mm, correlation coefficient of 0.96, percent error of 11.36, and model efficiency of 87.54%, for the watershed indicate reasonably accurate simulation of runoff by the model.
- The overall statistical model performance parameters namely RMSE of 0.33 Mg/ha, correlation coefficient of 0.85, percent error of 13.83 and model efficiency of 83.18%, for the watershed indicate reasonably accurate simulation of sediment yield by the model.
- The WEPP model performed well when applied to the watershed in Shivalik foothills, for simulation and quantification of runoff and sediment yield and hence, can be used for future field application in the area.

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APPENDICES

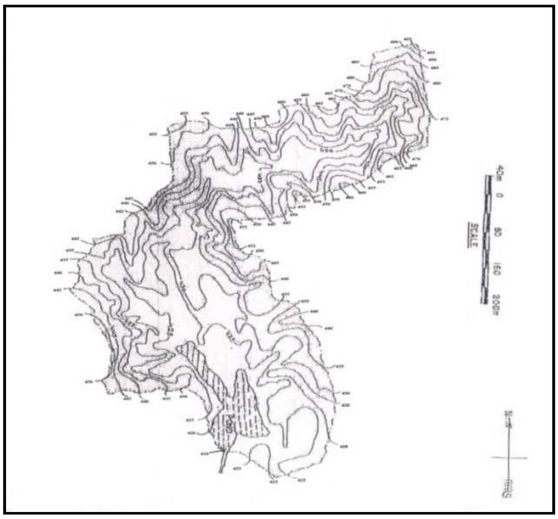

Figure 1: Topographic Map of Study Watershed

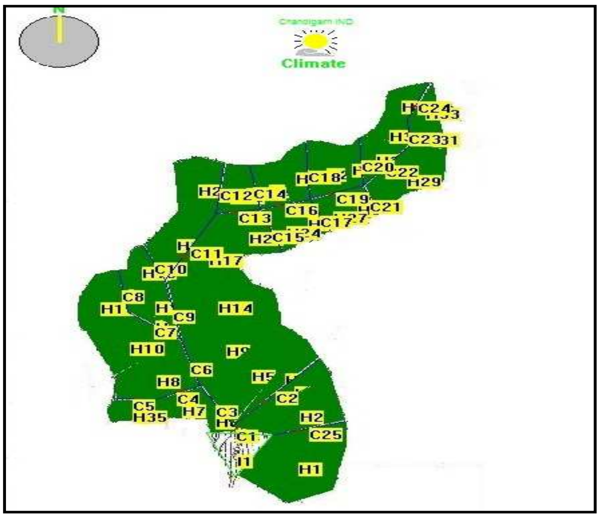

Figure 2: Delineated Hillslopes and Channels in the Watershed

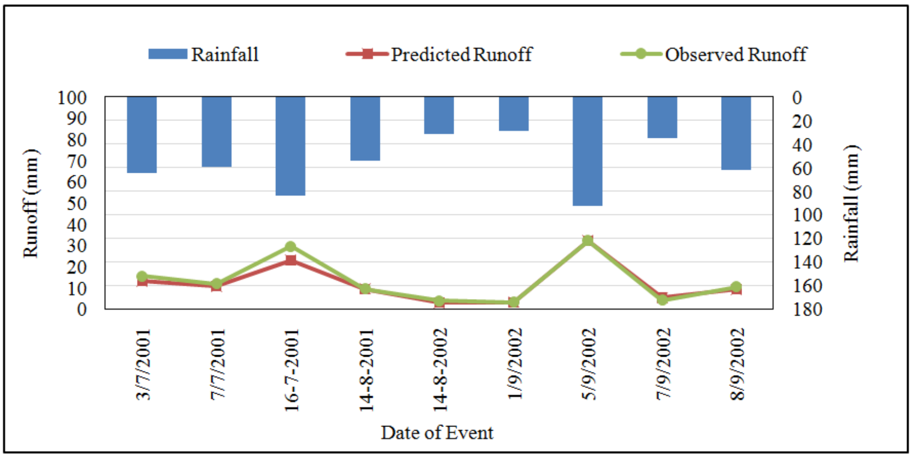

Figure 3: Observed and Predicted Storm Wise Runoff for Model Calibration

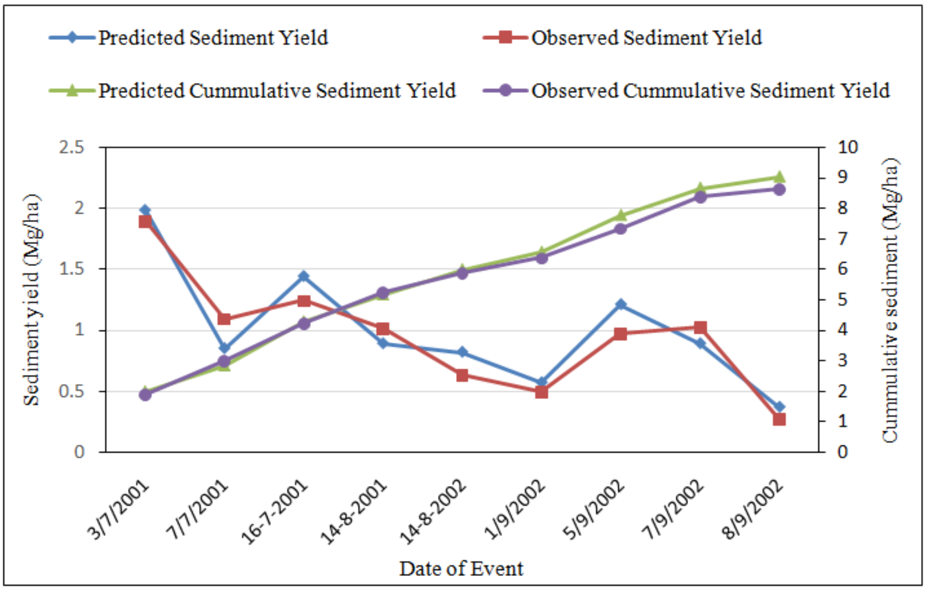

Figure 4: Observed and Predicted Storm Wise Sediment Yield for Model Calibration

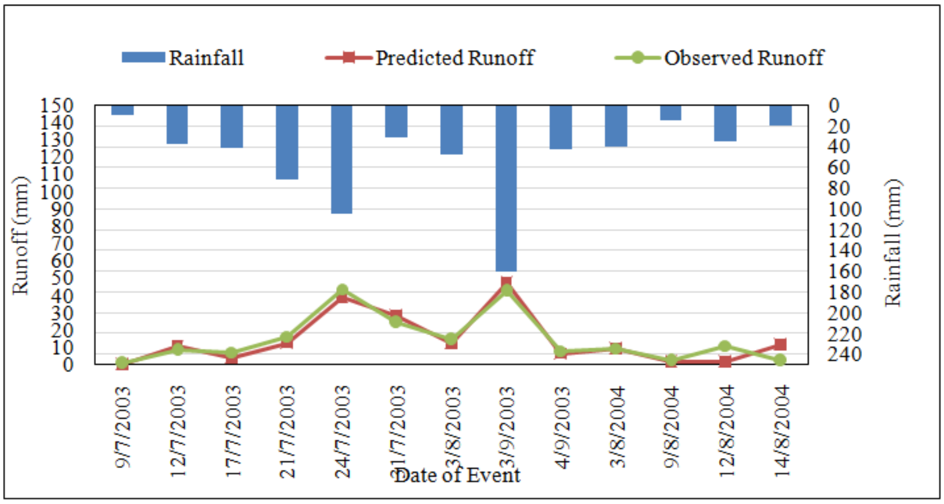

Figure 5: Observed and Predicted Storm Wise Runoff for Model Validation Period

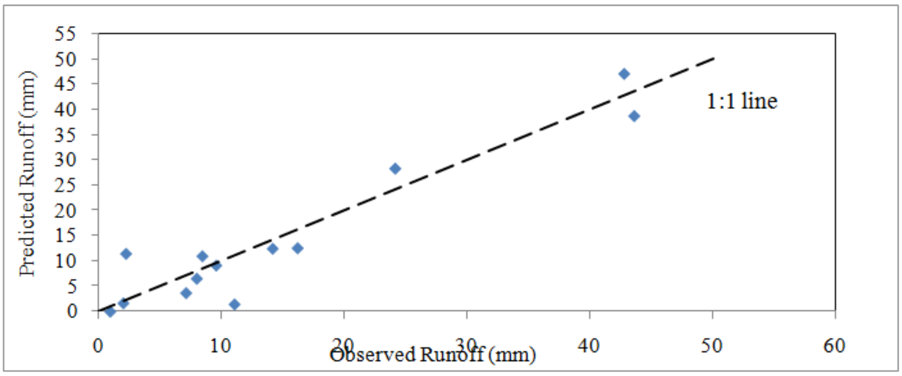

Figure 6: Comparison between Observed and Predicted Storm Wise Runoff for Model Validation

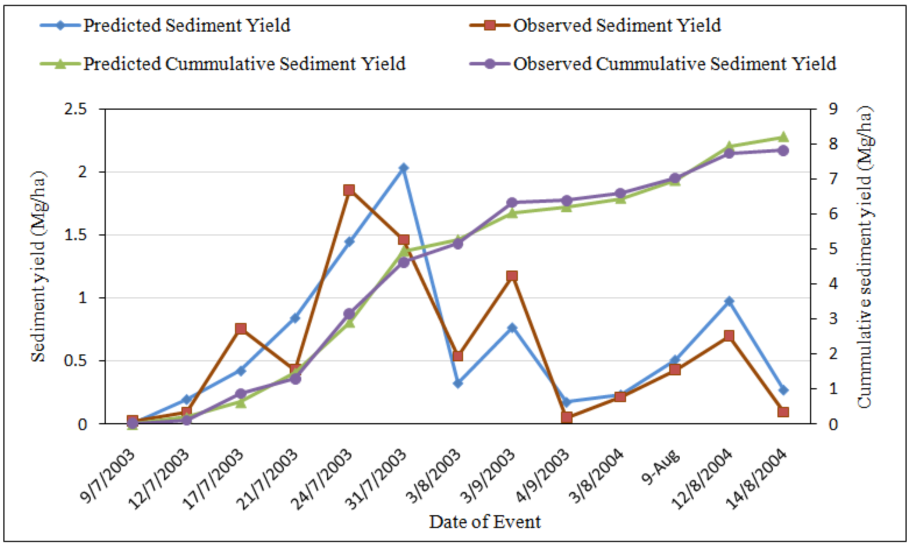

Figure 7: Observed and Predicted Storm Wise Sediment Yield for Model Validation

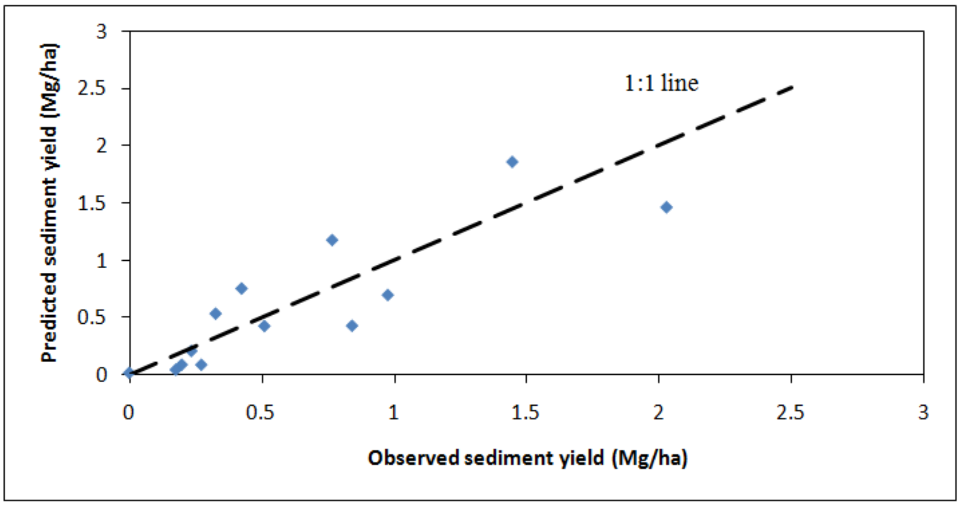

Figure 8: Comparison between Observed and Predicted Storm Wise Sediment Yield for Model Validation